On Isgur's "Critique of a Pion Exchange Model for Interquark Forces"

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Abstract

The conceptual issues of low-energy baryon physics are discussed. In particular, a comparison between the naive one gluon exchange model for the interaction between constituent quarks in hadrons and the Goldstone boson exchange picture is made. The "defects" of the Goldstone boson exchange model for baryons, indicated by Isgur [1] are examined in detail. *All* of the purported "defects" are shown to lack a valid basis.

PACS number(s): 12.39.Jh, 14.20.-c

1 Introduction

The recent "critique" [1] of the Goldstone boson exchange (GBE) model [2, 3] for the baryon spectra contains a number of strong and at the same time unsubstantiated statements. Given the author's "silence is consent" [1] and an increasing pressure from the community, a rebuttal has become unavoidable. In this rebuttal the structure of Isgur's paper [1] will be adhered to and his "catalogue of criticisms" will be examined. An updated version of the GBE model for the baryon spectrum is available in ref.[4]. We discuss conceptual issues related to a question of paramount importance: which physics, inherent in QCD, is responsible for the nucleon (baryon) mass and its low-energy properties and how this physics is connected with the observed baryon spectra.

In the introduction to the first variant of his paper Isgur [1] questions the superiority of the GBE model for solving the problem of the spectral ordering in light and strange baryons, and argues that the Coulomb component of the one gluon exchange (OGE) interaction naturally leads the positive parity state $N(1440)$ to be the lowest one among positive parity $N = 2$ band. This issue is dropped from the final variant, but as the problem of the relative ordering of the lowest positive-negative parity states is the key question for deciding which physical picture is responsible for baryon (nucleon) masses, we will shortly address it here.

In a model with a monotonic effective confining interaction between quarks in light and strange baryons, which is flavor- and spin-independent, and assuming that there are no residual interactions, the spectrum of the lowest lying baryons should be arranged into successive bands of positive and negative parity (Fig. 1). Empirically, however, the lowest excited levels in the spectra of nucleon, the Δ - resonance and Λ-hyperon, which are shown in Fig. 2, look quite different. It follows that a picture, in which all other possible interactions are treated as only residual and weak and represent only a perturbation cannot be correct.

In the other extreme case, with a very strong Coulomb interaction between quarks and without any confining force at all, the lowest excited positive and negative parity states should be degenerate in all flavor parts of the spectrum, as in the hydrogen atom. Experimentally, however, the positive parity state N(1440) lies $\sim$ 100 MeV below the negative parity multiplet N(1535)-N(1520), on the one hand, but on the other hand the lowest positive parity state in the Λ spectrum lies 100 - 200 MeV above the lowest negative parity doublet (Fig. 2). This rules out the hypothesis of a dominant Coulomb interaction. In addition, a model with no confining interaction, that relies exclusively on the Coulomb part of OGE, fails for the spectra of all other

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[1] See the first version of the paper which has become widely known and which can be extracted from the LANL e-print server as version 1.
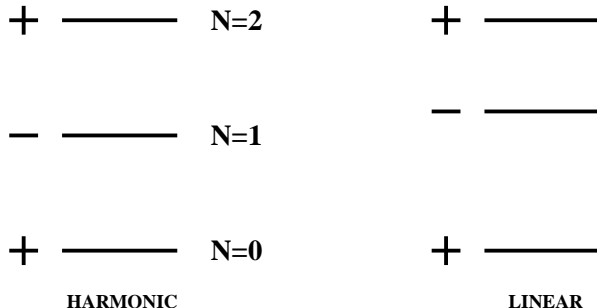
Figure 1: A sequence of positive and negative parity levels with harmonic and linear confining interactions.

low-lying baryons. Such a model cannot provide the required 500 MeV gap between the ground state baryons and the first negative parity excitation band. As soon as a confining interaction is added, irrespective of whether harmonic, linear or some other monotonic functional form, the Roper resonance (and its counterparts in other flavor parts of the spectrum) falls $\sim 100 - 300$ MeV above the negative parity multiplet, a result which is well known from many exact 3-body calculations, see e.g. [5, 6, 7], including those of Isgur [8].[2] It then follows that a combined model, relying on both the confinement potential and color-Coulomb component of one gluon exchange cannot explain the experimentally observed pattern.

The next important issue is how these spectra change when perturbed by the color-magnetic component of OGE. To leading order and when one ignores the spatial dependence of the color-magnetic interaction and assuming the $SU(3)_F$ limit, its contribution is determined exclusively by the spin structure of the zero-order baryon wave function, which is prescribed by the corresponding Young diagram. This spin structure is unambiguously determined by the total spin of three quarks. This spin is the same, $S = 1/2$, for all baryons in N and Λ spectrum, depicted in Fig. 2. This then implies that such a spin-spin force, which is not sensitive to the flavor of quarks, cannot modify the ordering of the states, suggested by the confinement + Coulomb interaction. If one takes into account a spatial dependence of the color-magnetic interaction as well as the $SU(3)_F$ breaking, its contribution to the positive

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[2]In Isgur's papers with Karl [9], the positive and negative parity states are treated separately in different papers, and a very strong color coupling constant - larger than 1 - is needed to fit the $N - \Delta$ mass splitting, which is incompatible with the perturbative treatment of QCD, and a huge anharmonic "correction" is introduced by hand in order to cure the positive parity states. This is the salient point as it is assumed in the Isgur-Karl model that the anharmonicity, i.e. difference between the harmonic interaction and the linear + Coulomb interaction could shift the Roper strongly down. This is excluded in exact three-body calculations [5, 6] and also at the theorem level - see [7] (and references cited therein).
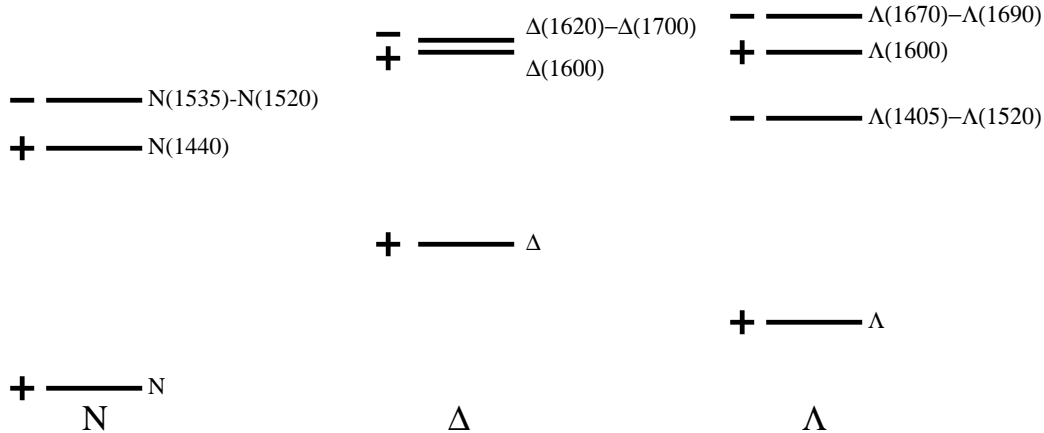
Figure 2: Low-lying spectra of nucleon, Δ-resonance and Λ-hyperon.

and negative parity states will be slightly different, because of the different radial structure of these baryons. Nevertheless, a first order perturbation calculation or nonperturbative calculations [5, 6, 8] reveal[3], that the departures from the pattern of Fig. 1 are small. But even more seveer is the constraint from the Δ spectrum. In this case the color-magnetic interaction shifts the $N = 2$ state $\Delta(1600)$ $(S = 3/2)$ up, but not down, with respect to the negative parity $N = 1$ pair $\Delta(1620) - \Delta(1700)$ $(S = 1/2)$! All these facts rule out the perturbative gluon exchange plus confinement picture as a physical mechanism for the generation of light baryon mass. These spectra obviously point to explicit flavor dependence in the underlying dynamics. The GBE force, which is explicitly flavor dependent, very naturally explains this as well as several other apparent puzzles[4][2, 3, 4].

But in a sense more important is the conceptual inadequacy of the simplistic OGE model. This model invokes constituent quarks as particles with constant mass, without any attempt to understand an essense of these objects, which is very different from that of the light current quarks of QCD. The constituent quark can be introduced as a quasiparticle in the Bogoliubov or Landau sense stemming from the dynamical chiral symmetry breaking in QCD and related to the quark condensate

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[3]Note that the theoretical predictions for all positive and all negative parity states are shifted down and up, respectively, in figures of the ref. [8], so after a reconstruction of actual picture as it follows from the Tables of that paper it is very difficult to conclude that a reasonable description of the spectra has been obtained!

[4]In fact, one needs only two parameters to explain the pattern of Fig. 2 in the most simple form of the GBE model [2]: the strength of the GBE-like interaction and the strength of the effective confining interaction [4]. This is in contrast to quite a misleading counting of the number of free parameters as done in a recent review [10].

in the QCD vacuum (in fact one cannot obtain a nonzero condensate without a dynamical mass of quarks). Such a dynamical mass is indeed observed on the lattice at small momenta where the nonperturbative phenomena become crucial [11, 12]. This physics is well known [13] and it is a common theme in all strongly interacting many fermion systems, to which QCD belong. The chiral symmetry breaking and the dynamical mass generation are inherently nonperturbative phenomena and cannot be addressed within perturbation theory. In perturbation theory the perturbative vacuum persists in any order and the quark condensate (as well as dynamical mass) are identically zero. It is therefore inconsistent to invoke of constituent quarks along with perturbative one gluon exchange. If one invokes constituent quarks, then one necessarily assumes the spontaneously broken mode of chiral symmetry, where the Goldstone boson field is required by the Goldstone theorem and the flavor-octet axial current conservation in the chiral limit implies the coupling of Goldstone bosons and quasiparticles [13, 20][5]. The fact that the typical momentum of valence *current* quarks in the nucleon is small, $\sim 100 - 200$ MeV, i.e. well below the chiral symmetry breaking scale, $\Lambda_\chi \sim 1$ GeV, implies that the low-energy characteristics of baryons, such as their masses, should be formed by the nonperturbative QCD dynamics that is responsible for the chiral symmetry breaking and confinement, but not by the perturbative QCD degrees of freedom which become active at much higher momentum scales. The effective meson exchange interaction between valence quarks in baryons arises from the nonperturbative t-channel iterations of the QCD gluodynamics which triggers the breaking of chiral symmetry and which is responsible for the low-lying meson structure [16]. This is a simple consequence of crossing symmetry: if one obtains the pion as a solution of the Bethe-Salpeter equation in the quark-antiquark s-channel, then one inevitably obtains pion exchange in the quark-quark systems as a result of iterations in the t-channel. What is important is that these t-channel iterations enormously reinforce the bare (gluonic) vertex in the GBE channel (which is due to the antiscreening) at small momenta. This antiscreening results in the pole that occurs at $q^2 = 0$. This pole "explosion" explains the role of the GBE interaction at low momenta, which dominates the low-energy baryon physics. Generation of the dynamical mass and the exchange by Goldstone bosons between quasiparticles in baryons are synchronous phenomena based on chiral symmetry breaking and cannot be separated from each other.

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[5]To avoid any confusion, one should not mix the one gluon exchange interaction between constituent quarks with its nonrelativistic spin-spin force, with the nonperturbative resummation of the gluonic exchanges between current quarks by solving the Dyson-Schwinger and Bethe-Salpeter equations, which could provide chiral symmetry breaking (this is one of the possibilities which is presently discussed [14]) and which will automatically lead to GBE between the quasiparticles in baryons upon t-channel iterations [16]. In this approach, however, the $U(1)_A$ problem persists and the origin of confinement is unclear. In this case the underlying mechanism for the $\pi - \rho$ splitting is the same like in Nambu and Jona-Lasinio model [15] and has nothing to do with the nonrelativistic spin-spin force between quarks.

There are many independent indications from spectroscopy that show that the physics in the heavy quark sector (where the chiral symmetry is absent and the confinement plus OGE picture is a relevant one) is very different from the light quark sector. For instance, the hyperfine (spin-spin) splittings in charmonium are of the order of 3% of the hadron mass, i.e. they indeed represent a small perturbation. In contrast, the spin-spin force in light baryons should be very strong as it provides splitting at the level of 30% of hadron mass ($N - \Delta$) splitting. The color-magnetic spin-spin interaction in the heavy quark systems has a clear origin as a small non-relativistic v^2/c^2 correction to the leading Coulomb force of OGE interaction, and, as it is well known from the positronium physics (which is similar) provides a small $\sim \alpha^4$ spin-spin splitting [17] and in the present case the values of v^2/c^2 , α^4 and the experimental splitting are all consistent to each other. In the light quark systems, the light current quarks with their tiny mass are ultrarelativistic. In this case the perturbative gluon - quark vertex to a good approximation conserves helicity (to be contrasted to heavy quark - gluon vertex), which implies that the spin dependence of OGE interaction vanishes in the present case [6]. This is in obvious conflict with the large empirical hyperfine $N - \Delta$ splitting and implies that the *perturbative* gluon exchange force cannot be its origin.

The lattice calculations indicate that the physics in the heavy quark sector is very different from the light quark sector. To these belong a recent analysis by Liu et al [18], showing that the origin of the $N - \Delta$ splitting is not due to the color-magnetic interaction, but inherently related with the dynamical chiral symmetry breaking and meson-like exchange force. The most recent work of RIKEN BNL - Columbia - KEK collaboration [19], which for the first time accurately measured the low-lying negative parity state[7] and also obtained a reliable signal for the Roper state, indicates that the dynamics for baryons made of heavy quarks (where the chiral symmetry and GBE-like force are absent), in which case the spectrum indeed looks like in Fig. 1, is very different from the real pattern in nature on Fig. 2, which is close to the chiral limit.

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[6] I repeat, once one considers the standard one gluon exchange perturbative force, then one assumes that we are in the perturbative regime of QCD, i.e. on the top of perturbative vacuum. Hence one can use only original (current) quarks of QCD in the present case.

[7]This can be considered as a proof that N(1535) is a genuine three quark resonance, but not a cusp due to the nearby $N\eta$ threshold and not a quasibound state in the meson-baryon system.

2 "The Spin-Orbit Problem is not Solved"

Here the argument made by Isgur is as follows. The empirical spectra of L=1 light baryons and mesons show no significant spin-orbit splittings. A scalar confining interaction implies a spin-orbit force due to Thomas precession, which should be cancelled by another spin-orbit force in both baryons and in mesons. Such an additional spin-orbit force is supplied by a strong one-gluon exchange interaction, while within the GBE model for baryons there is no source to counterbalance the Thomas term.

This argument is based on the naive extrapolation of heavy quark physics into the light quark sector. In the heavy quark systems, like charmonium or bottomonium, the most important dynamics is indeed due to the string-like confining force at large distances and a small perturbative gluon exchange correction at short ones. In this case a heavy quark practically constantly "sits" on the end of the string because a quantum-mechanical fluctuations of this quark into other one plus quark-antiquark pair (meson) are suppressed by the factor $1/M_Q$ (see footnote 14) and vanish in the heavy quark limit. This suppression factor comes from the meson propagator.

A relativistic rotation of the string implies the Thomas precession, which is a pure kinematical effect related to successive Lorentz transformations. This Thomas precession gives rise to a spin-orbit interaction. Note that for this effect to be operative it is necessary to have *the same* particle on the end of the string at the successive moments t_1, t_2 and t_3. For the heavy quark this condition is indeed approximately fullfilled.

In the light quark systems this condition is not satisfied, however. This is because quantum mechanical fluctuations of the light valence quark into the *other* quark and the light meson are not suppressed and become the most important effect. Within the quantum field theory such a fluctuation corresponds to materialization from the vacuum of the quark, which becomes the valence instead of the initial one, see Fig. 3. Because in the present case there is no big gap between the negative energy levels of the Dirac sea and the positive energy of the valence quarks, this process is intensive. This implies that at the successive moments t_1, t_2 and t_3 one has predominantly *different* quarks on the end of the string, though with exactly the same color. If quarks are different, the Thomas precession *cannot be applied*. In addition the spin of the quark at the moment t_2 is predominantly polarized just in opposite direction compared to the moments t_1 and t_3 as the pion-quark vertex is of spin-flip nature [22]. Thus, at t_2 the spin-orbit Thomas term is of opposite sign compared to that at t_1 and t_3[8]. This qualitative discussion suggests that the Thomas spin-orbit force should

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[8] One may speculate whether the loop fluctuation also affects the spin-spin force from the GBE between different quarks. The pion-quark vertex is of spin- and isospin-flip nature
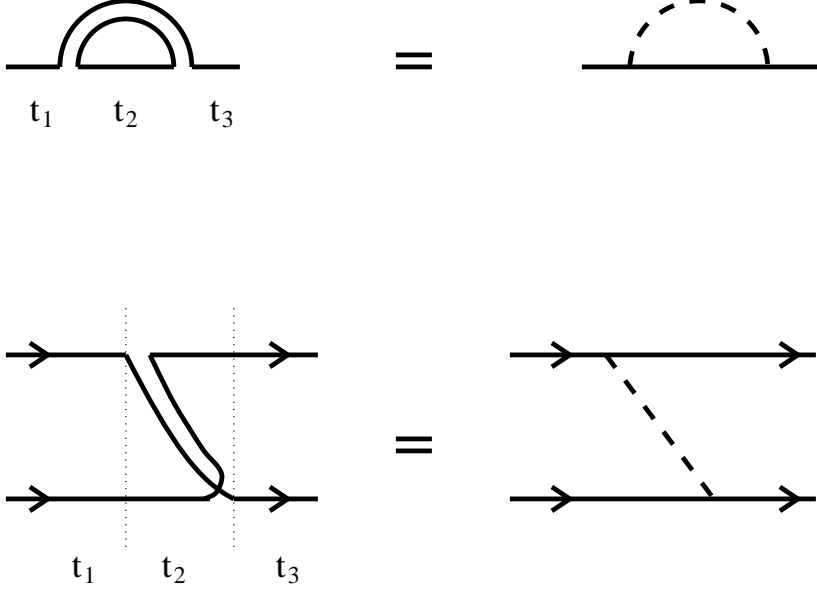
Figure 3: Pion fluctuation of the light constituent quark.

be strongly suppressed in the light quark systems, both in mesons and baryons[9].

If so, the spin-orbit force from the OGE which should be very strong as it is fixed by large $N - \Delta$ and $\pi - \rho$ splittings within the naive OGE model (combined with constituent quarks) completely destroys both baryon and meson spectra as it supplies splittings of *hundreds* MeV.

Based on the view of the near perfect cancellation of the very large, but opposite in sign, LS forces from Thomas precession and OGE interaction in P-wave light mesons (which, according to Isgur, should be of the same origin like in light P-wave baryons) , Isgur interpolates their matrix elements between the light and the heavy quarkonia to the heavy-light mesons and predicts a dramatic and large inversion of the spin-orbit splittings in the heavy-light P-wave mesons, where the data were absent (for details see ref. [23]). This prediction has recently been checked by two independent lattice groups [24] and has been ruled out. Not only does this prediction deviate from the data by a few hundreds MeV, but its sign is opposite!

In fact there do appear spin-orbit forces in the GBE model from the second iter-

which means that the loop contributions to the one pion exchange, where exchanged pion is attached to quark within a loop, produces the same operator $-\vec{\tau}_i \cdot \vec{\tau}_j \vec{\sigma}_i \cdot \vec{\sigma}_j$ as one pion exchange without loop.

[9]A detailed formal extension of this qualitative discussion will be published elsewhere.

ation of the interaction [2, 29, 30], which correspond to spin-orbit force from vector- and scalar-meson exchanges. Different meson exchanges provide the spin-orbit force with opposite signs in baryons [29, 30], which suggests that the net spin-orbit force should not be large, which is compatible with the small 10-50 MeV LS-splittings observed in L=1 light and strange baryons.

To conclude this section we stress that it is incorrect to identify the linear confining interaction between two heavy static sources, that is indeed established, with an effective confining interaction between the *quasiparticles* in the light quark systems.

3   "Baryon Internal Wave Functions are Wrong"

Here Isgur's argument is that while the OGE model yields a mixing of the spin $S = 1/2$ and $S = 3/2$ states in the $N(1535)$ and $N(1650)$ baryon wave functions, which is compatible with the big observed $N(1535) \rightarrow N\eta$ branching ratio and the small $N(1650) \rightarrow N\eta$ one, the GBE model should fail to do so.

This mixing above is provided by the tensor force component of the quark-quark force and crucially depends on its sign, while the masses of baryons are not strongly sensitive to this tensor force. Within the GBE picture there are two sources for tensor force: pion-like exchange and rho-like exchange mechanisms. Both of these exchanges supply a spin-spin force *with the same sign*, while their tensor force components have *opposite* signs [29]. This implies that the net tensor force should be rather weak compared to the strong spin-spin force, in agreement with phenomenology. In ref. [2] only a π-exchange tensor force was used for an estimate.[10] Its strength has not been correlated with the strength of the spin-spin force, which is fixed by the hyperfine splittings. As soon as the corresponding ρ-exchange like tensor force is added, the mixing becomes qualitatively different. The flavor dependent tensor force component of the two-pion exchange interaction (which is ρ-like) is, in the range relevant for the baryon wave functions stronger than that of the one-pion exchange interaction [30], and therefore the net tensor force, while weak, does have the sign opposite to that of pion exchange. The sign is then that, which is *favored* by the empirical mixing of the negative parity multiplets. Note that in the modern fits of baryon spectra both π-like and ρ-like exchanges are taken into account [4, 25, 29].

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[10] It has nevertheless been stressed there: "Any vector-octet-like exchange interaction component between the constituent quarks, would also reduce the net tensor interaction at short range as the contributions to the tensor interaction from pseudoscalar and vector exchange mechanisms tend to cancel, whereas they add in the case of the spin-spin component. These modification of the tensor interaction at short range may even lead to a sign change of the matrix element."

There are several indications that the ρ-like tensor force should dominate over the π-like in P-wave baryons. The analysis of the L=1 spectra and of the mixing angles for the flavor-dependent interaction [26] reveals that the tensor force that mixes $S = 1/2$ and $S = 3/2$ components should have a sign of the ρ-exchange tensor interaction[11]. With the flavor-dependent spin-spin and tensor force, with the matrix element being adjusted to provide the best χ^2 fit to baryon masses, a parameter-free prediction for mixing angle was obtained, which ideally fits the observed π and η decays branches for $J = 1/2$ and $J = 3/2$ $L = 1$ N^* baryons, discussed in Isgur's paper [1]. That work definitely shows that the fit of the observed $L = 1$ spectra prefers a flavor-dependent interaction between quarks.

This is perfectly consistent with the recent systematic $1/N_c$ analysis of both masses and mixing angles of L=1 nonstrange baryons [27]. The result of this paper may be summarized as follows: both masses and mixing angles extracted from the strong and electromagnetic decays are compatible with the idea that the effective quark-quark interaction is of meson exchange form, while they are not compatible with the flavor independent gluon exchange hyperfine interaction. In particular the data *require* the significant contribution of the operator that contains a flavor-dependent tensor force (O_3), while the contribution of the operator which represents a flavor-independent tensor force (O_8) is compatible with 0. Note that in the present analysis the contribution of different operators is systematically weighted with the N_c-dependent factor, which is absent in other more phenomenological analyses. The study of the πN phase shifts [28] also reveals that the spin-spin force between quarks should be of pion-exchange type, while the tensor force component should be of just opposite sign[12].

This should not be construed as a claim that a simple QQQ main component of the baryon wave function alone will be able to explain the variety of strong and electromagnetic decay data. The baryon wave function contains in addition further Fock components, $QQQ + meson, ...$ The coupling of these higher Fock components will be very important for strong decays in the case when the energy of the resonance is close to the corresponding threshold. In this case the energy denominator, which determines a role of the higher Fock component in the given reaction, e.g. in γN or $\pi N \rightarrow N(1535) \rightarrow N\eta$, becomes very small and the otherwise insignificant $QQQ\eta$ component of the $N(1535)$ wave function becomes important. This should

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[11]While this fact is not explicitly discussed in that paper, it follows from the mixing angles presented in Table 3 therein.

[12]Those authors actually conclude that the spin-spin force should be of pion-exchange type while the tensor force should of gluon-exchange type, which would be rather strange. But it is easy to see from their expressions that the same result will be obtained if one changes the sign of the single π-exchange tensor force to the opposite one.

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be a significant reason for why the η-decay branch is anomalously big in the case of $N(1535)$. Note that within the chiral constituent quark model this mechanism is very natural, while there are no meson components in the baryon wave function within the OGE model.

Similar arguments can be applied to explain an anomalously large $\Lambda(1405) - \Lambda(1520)$ spin-orbit splitting, because the $\Lambda(1405)$ is below the $\bar{K}N$ threshold and can be viewed as $\bar{K}N$ bound state [31]. If correct, it would simply mean that both coupled QQQ and $QQQK$ components are significant in the present case and there is no contradiction with the flavor singlet QQQ nature of these baryons, which in any case are LS partners with respect to their main QQQ component. The alternative explanation of the latter extraordinary large LS splitting would be that there is some rather large spin-orbit force specific to the flavor singlet state only [2, 26], which is also not rulled out, while it is clear that OGE cannot supply such a flavor dependent LS force. The mixing pattern of singlet and octet components that is obtained with the flavor-dependent interactions in ref. [26] better describes the strong decays of $\Lambda(1405)$ than that one obtained with the flavor-independent interaction.

To conclude this section one should stress that in the present state of the art it is premature to judge on the effective QQ interactions from the strong decays. This is, in particular, because the excited states are treated within the quark model as bound states, rather than as resonances, and an incorporation of the $QQQ\pi$,... continuum components coupled to the principal one QQQ is vital for strong decays. A real test of any constituent quark model beyond spectroscopy (i.e. also of their wave functions) can reliably nowadays be performed only for the ground state observables. Such a task has just been completed for the chiral constituent quark model [32]. Starting out from the wave functions obtained in ref. [3], which represent the eigenstates of the mass operator of the manifestly covariant point form of relativistic quantum mechanics, one has calculated nucleon e.m. formfactors performing relativistic boost transformations [33]. The *parameter free* predictions for proton and neutron electric and magnetic formfactors as well as charge radii and magnetic moments turned out very satisfactory and practically explain existing data (e.g. within the experimental error bars for proton and neutron charge formfactors). It is also demonstrated that using the same wave functions but a nonrelativistic framework for calculating these observables, the formfactors and charge radii result completely differently, deviating by 1-2 orders of magnitude. From this comparison one can conclude, in particular, that the proper inclusion of Lorentz boosts is crucially important. In view of all that nonrelativistic calculations within the constituent quark models (or similarly within bag models), appear very questionable. This is especially true with regard to strong decays.
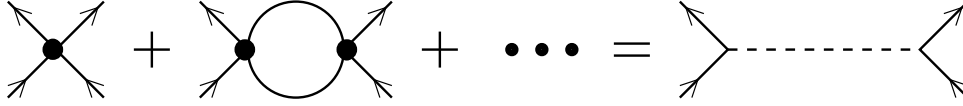
Figure 4: Iteration of the instanton-induced 't Hooft interaction (or some other gluonic interaction which is responsible for the chiral symmetry breaking in QCD) in the qq t-channel in baryons. Black filled circle means a bare gluonic vertex.

4 "Mesons are Disaster"

There are several arguments suggested by Isgur in this section. The first one is that while the GBE (or, generally, meson exchange like interactions) may be possible in baryons, such are impossible between valence quark and antiquark in mesons (e.g. in $u\bar{d}$ pair) within the quenched approximation to QCD, thus suggesting that meson and baryon spin-dependent interactions must have totally different physical origins which is very difficult to arrange.

This question has been addressed in detail recently [16]. I will briefly summarize here the main conclusions. One needs a nonperturbative gluonic interaction between quarks in QCD to provide chiral symmetry breaking. A good candidate is the instanton-induced 't Hooft interaction [34, 21, 35]. When this nonperturbative gluonic interaction breaks chiral symmetry, i.e. generates at low momenta the constituent mass m of quarks, it also automatically supplies a strong attractive interaction in the pseudoscalar-isovector quark-antiquark system - pions - which makes them anomalously light, with zero mass in the chiral limit. This is how the pions appear as the Nambu-Goldstone bosons of the spontaneously broken chiral symmetry. This mechanism is well illustrated by the Nambu and Jona-Lasinio model [13]. While there is a strong attractive interaction in the pseudoscalar-isovector quark-antiquark system, the interaction is *absent* to leading order in vector mesons, which means that masses of vector mesons should be approximately $2m$, which is well satisfied empirically, $\mu_\rho \simeq \mu_\omega \simeq 2m$. The implication is that the $\pi - \rho$ mass splitting is not due to the perturbative color-magnetic interaction between spins of constituent quarks in π and ρ, but entirely due to the fact that the QCD Lagrangian posseses a chiral symmetry which is dynamically broken in the QCD vacuum. Note that the 't Hooft interaction also naturally solves the $U(1)_A$ problem, explaining thus why η' is heavy, contrary to π. This problem cannot be solved by the OGE interaction as a matter of principle.

The Nambu and Jona-Lasinio mechanism of chiral symmetry breaking (and hence of $\pi - \rho$ splitting) is the most general one. It only exploits the fact that the quark-

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gluon interaction in QCD respects chiral symmetry. In fact one does not need to assume that it is the instanton-induced interaction which provides chiral symmetry breaking.

When that nonperturbative gluonic interaction between quarks, which is responsible for chiral symmetry breaking in QCD, is iterated in the qq t-channel in baryons, it inevitably leads to poles which correspond to a GBE interaction in quark-quark pairs, see Fig. 4. This is a typical antiscreening behavior, the interaction of two quarks in baryons is represented by a bare gluonic vertex at large momenta transfer (i.e. at very small distances), but it blows up at small momenta in the channel with GBE quantum numbers, explaining thus a distinguished role of the latter interaction in the low-energy regime. Thus the GBE interaction in baryons is in fact an effective representation of the t-channel ladders, which strongly reinforce a bare gluonic vertex at low-momentum transfer in the GBE channel. Since the typical momentum of valence current quarks in baryons is well below the chiral symmetry breaking scale, these interactions dominate (see Introduction). This suggests that the origin of the hyperfine splittings in both the low-lying mesons and baryons is intrinsically the same - it is the nonperturbative gluonic interaction between quarks which is responsible for chiral symmetry breaking in QCD - which, however, reveals itself differently in mesons and baryons.

In Fig. 2 of his paper Isgur shows an evolution of the hyperfine splittings in mesons starting from the heavy quarkonium to $\pi - \rho$ mass splitting, arguing that it supports "a smooth evolution of the wave function ... convoluted with the predicted $1/m_Q^2$ strength of the OGE hyperfine interaction". This figure is misleading. Even if one takes a naive view that the $\pi - \rho$ splitting is due to OGE spin-spin force between the constituent quarks, one cannot explain why the pion is very light, but η, η' are heavy since this spin-spin force *must provide* the same strong attraction also in η, η', or, in other words, one cannot explain in this approach why $\pi - \rho$ mass splitting is big but $\eta' - \frac{\sqrt{2}\omega + \phi}{\sqrt{3}}$ mass splitting is even opposite in sign. This fact alone rules out this naive mechanism of the light pseudoscalar-vector meson splittings.

The Fig. 3a of Isgur's paper claims to support the same idea using the heavy-light mesons. According to Isgur this figure illustrates the $1/m_q$ behaviour of the OGE spin-spin force splittings, where m_q is light quark mass. Again, this figure is as misleading as the previous one, as it does not show really *clean*[13] examples which rule out this behavior. To these belong the hyperfine $D - D^*$ splitting of 141.4 MeV and $D_S - D_S^*$ one of 143.8 MeV. In the former case one has $\bar{c} - u$ or $\bar{c} - d$ system, while in the latter one the u or d quark is substituted by a strange one. One obviously ob-

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[13]The transition from the $B - B^*$ and $D - D^*$ systems to $K - K^*$ and $\pi - \rho$ is dubious one as in the former case the system is indeed heavy-light, while in the latter it is light-light.

serves an absence of the $1/m_q$ behaviour as the constituent light and strange masses differ by 30 - 50 %. Exactly the same situation takes place in B-meson, compare the hyperfine $B - B^*$ splitting of 45.7 MeV with that one of $B_S - B_S^*$, of 47.0 MeV. One can then conclude that while there is indeed the $1/m_Q$ scaling with respect to heavy quark mass m_Q in the heavy-light systems, which follows from the heavy quark limit (symmetry) in QCD [38], there is *no* similar behavior with respect to light quark component of the heavy-light systems. Similar objections can be raised against Fig. 3,b of Isgur's paper.

Needless to say that the Isgur's statement about the large $\pi - \rho$ mass splitting as originating in the nonrelativistic spin-spin force component of OGE *perturbation* comes into conflict with the current algebra and all subsequent developments in QCD which show unambiguously that the low mass of pion, which is approximate Goldstone boson (and which is of course a quark-antiquark system), is due to the chiral symmetry dynamical breaking in the QCD vacuum. Even if one assumes that the dynamical chiral symmetry breaking comes from the nonperturbative resummation of gluonic exchanges by solving the Dyson-Schwinger equation for the quark Green function and the low mass of pion from a simultaneous solution of the Bethe-Salpeter equation for the quark-antiquark system with the gluon-exchange kernel, the low mass of the pion (and $\pi - \rho$ splitting) in this case has nothing to do with the quark-antiquark nonrelativistic spin-spin force (see footnote 5).

However, it is indeed the case that the small hyperfine splittings in the heavy quarkonia are due to the nonrelativistic color-magnetic spin-spin force stemming from the small OGE perturbation. This mechanism, while important at the botom and charm quark mass scales, dies out in the region between the charm and strange quark scales (it vanishes in the chiral limit). On the other hand near the chiral limit the splittings are due to the chiral symmetry dynamical breaking, which, in turn, should decrease with increasing the current quark mass. It then follows that the smooth evolution of the splittings shown in Figs. 2 and 3 of Isgur's paper, is due to a superpositions of these two pictures.

Next Isgur argues that the annihilation graphs, see his Fig. 4, which are possible only in the isoscalar channels in mesons, but not possible in the isovector ones and which violate the OZI rule should produce strong splitting in $\rho - \omega$ system as well as a strong mixing of the $\bar{u}u, \bar{d}d$ and $\bar{s}s$ components in ω and ϕ, if one assumes that the GBE graphs between quarks in baryons induce a $\Delta - N$ splitting. This problem has a very simple resolution if one assumes that the instanton - induced 't Hooft interaction is the most important one. These annihilation graphs do contribute in the pseudoscalar mesons and provide the solution of the $\pi - \eta - \eta'$ puzzle. However, there are *no* such graphs from 't Hooft interaction in vector mesons [36, 35]. It is

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this pecuilarity which explains the completely different mixing of singlet and octet components in the pseudoscalar and vector mesons, which is unnatural in the former case and natural in the latter one [36]. As explained in the beginning of this section the GBE interaction in the quark - quark systems (to be contrasted to the quark - antiquark ones) can be regarded a result of the t-channel iterations of the same (like in mesons) bare 't Hooft vertex.

5   "The Connection to Heavy Quark Baryons is Lost"

Here Isgur again uses his Figs. 2 and 3 for argumentation.

While it is correct that around the heavy quark limit the OGE mechanism is indeed important for small hyperfine splittings, the light quark limit (chiral limit) is just opposite one in QCD and implies completely different dynamics, inherent in QCD. There are no doubts that it is a chiral dynamics, i.e. dynamics of massless quarks in external gluonic fields which becomes the most important phenomenon in this case. As argued in the previous section no conclusions can be obtained from these figures, which ignore well known empirical data.

What then the dynamics is, that is responsible for the heavy - light systems, and, in particular, heavy-light baryons[14] is an open question (it cannot be excluded that in the case of baryons both meson-like dynamics and perturbative QCD corrections are equally important). At least, what is known, the prediction of the spin-orbit splittings in heavy-light mesons [23], based on the scalings of Figs. 2 and 3 and OGE, turned out in dramatic disagreement with the very recent lattice results [24].

Returning then to the question of the splitting of the $\Lambda(1405) - \Lambda(1520)$ multiplet and its charm analog $\Lambda_c(2954) - \Lambda_c(2627)$ there is no objection to their dynamical similarity, which suggests that the $\Lambda(1405)$ should have a large QQQ component. As explained in the section 3, it does not contradict the idea that there is

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[14]It is, unfortunately, an incorrect statement in [1] that the exchange by heavy-light meson (e.g. D, D^*) between heavy-light quark pairs in baryons [37] should produce $1/M_Q^2$ scaling, in contradiction with the heavy quark limit. Naively, from the covariant meson propagator one would indeed obtain scaling $1/M_Q^2$. This scaling comes from both the positive energy solution propagating forward in time and the negative energy solution propagating backward in time. However, the "heavy meson exchange" viewed as in Fig. 3 with the Z-like part made of the light quark line only and with the heavy quark propagating only forward in time scales as $1/M_Q$. The heavy quark Z-like line , which would correspond to the propagation of the heavy quark backward in time, is suppressed by heavy quark mass.

an appreciable higher Fock component $QQQ\bar{K}$, which provides an anomalously large $\Lambda(1405) - \Lambda(1520)$ splitting. The other possibility, that there exists some spin-orbit force, which is specific to the flavor - singlet state only is also not ruled out, while it is clear that OGE, which is flavor independent, cannot provide such a spin-orbit force.

6 Conclusions

In "Conclusions" Isgur raises a few conceptual objections. The first one is about a double-counting problem since a theory which uses both constituent quarks and Goldstone bosons has "both fundamental Goldstone bosons and quark-antiquark bound state Goldstone bosons".

This objection is obviously based on misunderstanding of the low-energy effective theory. There is no fundamental Goldstone boson field in QCD. The pion as a Goldstone boson is of course a system of quarks and antiquarks and has entirely dynamical origin [13]. It arises naturally as a deeply bound state from the corresponding microscopical quark-gluon nonperturbative interaction in QCD, e.g. the instanton - induced one. When one applies the same Lagrangian (which does not contain any pion field!) in baryons and iterates it in the qq t-channel, one arrives at the pole contribution which corresponds to GBE between quarks in baryons [16]. This is a simple consequence of crossing symmetry: if one obtains pion as a solution of the Bethe-Salpeter equation in the quark - antiquark s - channel, then one inevitably obtains a pion - exchange in the quark - quark systems as a result of iterations in the qq t-channel. There is no fundamental pion-exchange between quarks as there is no fundamental pion field in QCD. The pion exchange is not more than an effective representation of the t-channel ladders in the low-energy and low-momentum regime where these ladders become important.

The second problem "is that it is not legitimate to treat the quark-Goldstone boson vertex as pointlike". In fact that was never suggested and instead it has been insisted, in all papers, that the finite size of both constituent quarks and pions provides a smearing of the otherwise contact short-range spin-spin quark-quark force. It is this smeared short-range part of GBE interaction that is crucially important for splittings in baryons. Indeed, the results crucially depend on the smearing parameter [3], that should be originated from the intrinsic structure of pion and also from unknown nonlinear behavior of the effective chiral Lagrangian [39].

The third objection that "there is no obvious rationale for truncating the tower of meson exchanges ..." was addressed in the section 3. Obviously all mesons should contribute. An important issue, however, is that the spin-spin force from π, ρ or a_1

meson exchanges in quark-quark system has exactly the same flavor-spin structure and sign at short range, which is crucial for baryon spectroscopy, so they only enhance the effect of each other, while the tensor and spin-orbit forces from different meson exchanges interfere destructively in baryons [29], which explains a significant spin-spin force and at the same time rather weak net tensor and spin-orbit forces, which is suggested by empirical baryon spectra. Nevertheless, the importance of different meson exchanges is different and is determined by the position of the corresponding pole at the unphysical time-like momenta in the quark-quark system (i.e. in baryon). The closer a pole is to the space-like region, which determines the quark-quark interaction, the more important the given meson exchange is. The pion pole is located just at the origin of the space-like axis and thus strongly influences the quark-quark interaction in baryons in the regime where momentum transfer is not large.

In summary the idea of the GBE model in baryons is not that there is no perturbative gluon exchange in QCD and, in particular in light baryons and mesons, but that such contributions cannot be significant for the *low-energy* observables such as masses, where the dynamics is driven by nonperturbative phenomena among which the crucially important are dynamical chiral symmetry breaking and confinement. The importance of the GBE flavor-dependent spin-spin force is not only conceptually substantiated, but it is also strongly supported by the fact that once one extracts the pion-quark coupling constant from the well known pion-nucleon one, regularizes the πq vertex with the cutoff of the order $\Lambda_\chi \sim 1$ GeV and solves the (semi)relativistic 3-body equations exactly, the $N - \Delta$ splitting turnes out of the order 300 MeV (or larger!). At the same time the Roper state is shifted down below the negative parity multiplet. The addition of any sizable phenomenological color-magnetic force between the constituent quarks explodes the baryon spectra [40].

7   Acknowledgement

I am grateful to D.O. Riska for a careful reading of the manuscript.

References

[1] N. Isgur, Phys. Rev. **D62** 054026 (2000); nucl-th/9908028 (versions 1 and 2).

[2] L. Ya. Glozman and D. O. Riska, Phys. Rep. **268**, 263 (1996).

[3] L. Ya. Glozman, W. Plessas, K. Varga, and R. Wagenbrunn, Phys. Rev. **D58** 094030 (1998)

[4] L. Ya. Glozman, Plenary talk given at PANIC 99, Nucl. Phys. **A663,664** 103c (2000).

[5] J. Carlson, J. Kogut, and V.R. Pandharipande, Phys. Rev. **D27**, 233 (1983)

[6] B. Silvestre-Brac and C. Gignoux, Phys. Rev. **D32**, 743 (1985)

[7] G. Karl and V.A. Novikov, Phys. Rev. **D51**, 5069 (1995)

[8] S. Capstick and N. Isgur, Phys. Rev. **D34**, 2809 (1986)

[9] N. Isgur and G. Karl, Phys. Rev. **D18**, 4187 (1978);**D19**, 2653 (1979)

[10] S. Capstick and W. Roberts, nucl-th/0008028

[11] S. Aoki et al, Phys. Rev. Lett. **82**, 4592 (1999)

[12] J. I. Skullerud and A. G. Williams, hep-lat/0007028

[13] Y. Nambu and G. Jona-Lasinio, Phys. Rev. **122** 345 (1961); **124** 246 (1961)

[14] C. D. Roberts and A. G. Williams, Progr. Part. Nucl. Phys., **33**, 4777 (1994)

[15] U. Vogl and W. Weise, Progr. Part. Nucl. Phys. **27** 195 (1991); S. P. Klevansky, Rev. Mod. Phys., **64** 649 (1992); T. Hatsuda, T. Kunihiro, Phys. Rep. **247** 221 (1994).

[16] L. Ya. Glozman and K. Varga, Phys. Rev. **D61**, 074008 (2000)

[17] L. D. Landau and E. M. Lifshitz, Course of Theoretical Physics, vol. 4, Pergamon Press, 1982

[18] K. F. Liu et al, Phys. Rev. **D59** 112001 (1999)

[19] S. Sasaki, hep-ph/0004252

[20] A. Manohar and H. Georgi, Nucl. Phys. **B234** 189 (1984).

[21] D. Diakonov and V. Yu. Petrov, Nucl. Phys. **B272** 457 (1986).

[22] L. Hannelius, D.O. Riska and L. Ya. Glozman, Nucl. Phys. **A 665** 353 (2000)

[23] N. Isgur, Phys. Rev. **D57** 4041 (1998)

[24] R. Lewis and R. M. Woloshin, hep-lat/0003011

[25] R. Wagenbrunn, L. Ya. Glozman, W. Plessas, K. Varga, Nucl. Phys. **A 663,664** 703c (2000)

[26] H. Collins and H. Georgi, Phys. Rev. **D59** 094010 (1999)

[27] C. E. Carlson et al, Phys. Rev. **D59** 114008 (1999); C. D. Carone, hep-ph/0004216

[28] T. Yoshimoto, T. Sato, M. Arima, T.-S.H. Lee, nucl-th/9908048

[29] L. Ya. Glozman, Surv. High Energy Phys., **14** 109 (1999); hep-ph/9805345

[30] D. O. Riska and G. E. Brown, Nucl.Phys. **A653** 251 (1999)

[31] R. H. Dalitz and A. Deloff, J. Phys. **G17** 289 (1991) and references therein.

[32] R. F. Wagenbrunn et al, to be published

[33] W. H. Klink, Phys. Rev. **C58** 3587 (1998); **C58** 3617 (1998)

[34] G. 't Hooft, Phys. Rev. **D14** 3432 (1976)

[35] T. Schäfer, E. V. Shuryak, Rev. Mod. Phys., **70** 323 (1998)

[36] G. 't Hooft, hep-th/9903189

[37] L. Ya. Glozman and D. O. Riska, Nucl. Phys. **A603** 326 (1996) [E: ibid **A620** 510 (1997)

[38] N. Isgur and M. B. Wise, Phys. Lett. **B232** 113 (1989); **B237** 527 (1990)

[39] L. Ya. Glozman, Phys. Lett. **B459** 589 (1999)

[40] L. Ya. Glozman, Z. Papp, W. Plessas, K. Varga, R. Wagenbrunn, Phys. Rev. **C57** 3406 (1998).